

Physics-based Noise Simulation of Semiconductor Devices Under Large-signal Operation

Original

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**EDS Mini-Colloquium On
Advanced Electron Devices modelling and Technology**

Friday 1st May 2009. Admission is free

University College Dublin, Ireland

(Engineering Building (no 49 on the campus map))

Sponsored by

IEEE Electron Devices Society, IEEE UKRI (AP/ED/Photonics/MTT) Societies Joint Chapter

09:15 – 09:50 Registration

09:50 – 10:00 Welcome Remarks: Prof Tom Brazil, University College Dublin

10:00 Opening Remarks: Prof Ali A Rezazadeh, Chair IEEE UKRI (AP/ED/Photonics/MTT) Societies Joint Chapter, University of Manchester, UK.

10:10 IEEE EDS Activities: Prof J J Liu (Central University of Florida, USA)

10:30 – 12:45 SESSION I

Chair: Prof. Giovanni Ghione

10:30 – 11:15: Roadmap for 22 nm and Beyond, Prof Hiroshi Iwai (Tokyo Institute of Technology, Yokohama, Japan)

11-15 – 12:00: Small- and Large-Signal Modelling of GaAs- and GaN-based Transistors
Prof Tom Brazil (University City Dublin, Ireland)

12:00 – 12:45: Advanced electrostatic discharge (ESD) protection solutions in
BiCMOS/CMOS technologies, Prof J J Liu (University of Central Florida, USA)

12:45 – 2:00: **Lunch Break**

02:00 – 02:30: PhD Research Students Poster Session

02:30 – 04:20: SESSION II

Chair: Prof Tom Brazil

02:30 – 03:15: Physics-based Noise Simulation of Semiconductor Devices Under Large-signal Operation, Prof Giovanni Ghione, Fabrizio Bonani and Simona Donati Guerrieri (Politecnico di Torino, Italy)

03-15 – 04:00: Passive 3D multilayer microwave components for development of compact multifunctional MMICs, Prof Ali A. Rezazadeh (University of Manchester, UK)

04:00 – 04:20: Closing Remarks: Prof Hiroshi Iwai (Tokyo Institute of Technology, Japan)

For further information, please contact Prof. Tom Brazil, +353-1-716 1929, tom.brazil@ucd.ie

Physics-based Noise Simulation of Semiconductor Devices Under Large-signal Operation



G. Ghione, F. Bonani, S. Donati
Guerrieri

*Dipartimento di Elettronica,
Politecnico di Torino, Torino, Italy*

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Outline

- Motivation
- Overview on numerical noise modelling
 - Small-signal (stationary)
 - *Forced* large-signal (cyclostationary)
 - *Autonomous* large signal
- Modeling low frequency noise
- Evaluating the Large Signal working point
- Case studies
- Conclusions

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Motivation

- Low-noise circuits important in RF & microwave telecommunication systems
 - **Linear** circuits (e.g., low noise amplifiers)
 - **“Nonlinear”** circuits (e.g., mixers, frequency multipliers, oscillators)
- Physics-based simulation is a powerful tool for:
 - TCAD Device design and optimization
 - Development of compact, circuit-oriented model with sound physical basis
 - Understanding exotic noise mechanisms (1/f?)

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Some facts about physics-based numerical noise modelling - I

- Microscopic (carrier **velocity** or **population**) fluctuations are a *small perturbation* of
 - **DC steady-state** → *Small-signal, stationary noise*
 - **Large-signal (quasi) - periodic steady state** → *LS (quasi)-cyclostationary noise*
 - **LS steady-state of autonomous system** → *LS (oscillator) stationary (?) noise*

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Some facts about physics-based numerical noise modelling - II

- Terminal (v,i) fluctuations are evaluated through a (*linear*) **Green's function approach** from (spatially uncorrelated) microscopic (charge or current density) fluctuations distributed in the device volume
 - **SS conditions** → Superposition + *Filtering of microscopic noise source spectra*
 - **LS conditions** → Superposition + *Filtering & frequency conversion*

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Some facts about physics-based numerical noise modelling - III

- The **Green's function** (→ “impedance field”) can be derived through SS (small-signal) or SSLS (ss with respect to LS) linearization from **any PDE based physical model**:
 - Drift-diffusion
 - Energy balance
 - Full hydrodynamic, *N* moments from BE

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Summary of simulation steps

1. Evaluate the **noiseless working point**

- Noise sources are **switched off**
- Solution is $(\varphi_0, n_0, p_0, n_{t,k0})$
- The working point depends on the applied generators → **might depend on time and require mixed-mode simulation** → CPU-intensive for the large-signal case

2. Add (model) the **microscopic noise sources**

- The working point is perturbed by **fluctuations $\delta\alpha$**

3. Solve the (linear) perturbed system to evaluate the **terminal electrical fluctuations** (noise generators) through the Green's function approach

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Example: DD model, SS noise

$$\varepsilon \nabla^2 \Psi = -\rho(n, p, \Psi)$$

$$\frac{\partial n}{\partial t} = -\frac{1}{q} \nabla \cdot \vec{J}_n - U_n$$

$$\frac{\partial p}{\partial t} = +\frac{1}{q} \nabla \cdot \vec{J}_p - U_p$$

- Linearization around DC steady state, frequency domain & **Langevin sources**

Scalar & vector
Green's functions

$$\begin{cases} G_\alpha(\vec{r}, \vec{r}_1) \\ \nabla_{\vec{r}_1} G_\alpha(\vec{r}, \vec{r}_1) \end{cases}$$

$$\alpha = n, p$$

$$\varepsilon \nabla^2 G_\alpha = -\Lambda_\Psi(\tilde{n}, \tilde{p}, G_\alpha)$$

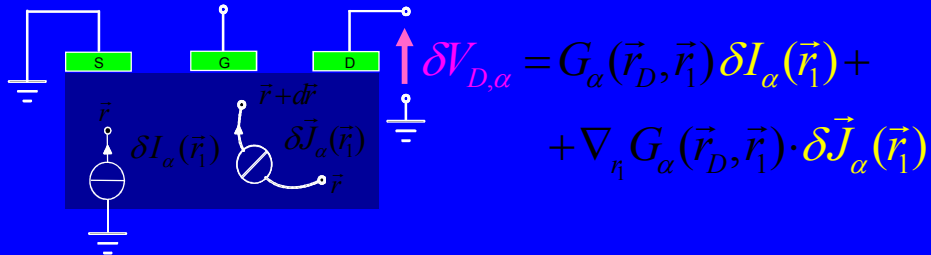
$$j\omega \tilde{n} = -\Lambda_n(\tilde{n}, \tilde{p}, G_\alpha) + \delta_{\alpha,n} \delta(\vec{r} - \vec{r}_1)$$

$$j\omega \tilde{p} = -\Lambda_p(\tilde{n}, \tilde{p}, G_\alpha) + \delta_{\alpha,p} \delta(\vec{r} - \vec{r}_1)$$

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Propagating fluctuations to terminals



$$\delta V_{D,\alpha} = G_{\alpha}(\vec{r}_D, \vec{r}_1) \delta I_{\alpha}(\vec{r}_1) + \nabla_{\vec{r}_1} G_{\alpha}(\vec{r}_D, \vec{r}_1) \cdot \delta \vec{J}_{\alpha}(\vec{r}_1)$$

$\delta I_{\alpha}(\vec{r}_1) \rightarrow \text{e/h GR noise source (population fluctuations)}$
 $\delta \vec{J}_{\alpha}(\vec{r}_1) \rightarrow \text{e/h diffusion noise source (velocity fluctuations)}$

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SS noise power spectra

- Correlation matrix of open-circuit voltage noise fluctuations:

$$S_{\delta V_i \delta V_j}(\omega) = \sum_{\alpha=n,p,\Omega} \int_{\Omega} \vec{G}_{\alpha}(\vec{r}_i, \vec{r}, \omega) \cdot \mathbf{K}_{\delta \vec{J}_{\alpha} \delta \vec{J}_{\alpha}}(\vec{r}, \omega) \cdot \vec{G}_{\alpha}^*(\vec{r}_j, \vec{r}, \omega) d\vec{r} + \sum_{\alpha,\beta=n,p,\Omega} \int_{\Omega} G_{\alpha}(\vec{r}_i, \vec{r}, \omega) K_{\gamma_{\alpha} \gamma_{\beta}}(\vec{r}, \omega) G_{\beta}^*(\vec{r}_j, \vec{r}, \omega) d\vec{r}$$

$$\mathbf{K}_{\delta \vec{J}_{\alpha} \delta \vec{J}_{\alpha}} = 4q^2 \alpha \mathbf{D}_{\alpha} \rightarrow \text{e/h diffusion local noise source}$$

$$K_{\gamma_{\alpha} \gamma_{\beta}}(\vec{r}, \omega) \rightarrow \text{e/h GR local noise source}$$

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LS cyclostationary noise - I

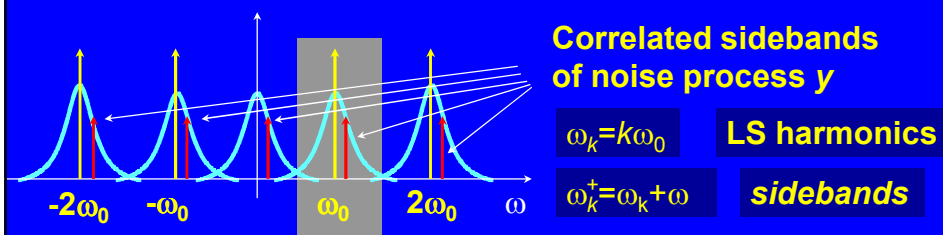
- Analog applications often require **periodic** or **quasi-periodic** LS operation
- In LS operation microscopic noise sources are **amplitude modulated** by the periodic LS steady-state leading to → **cyclostationary microscopic sources** with **correlated** frequency components
- Those are described by the **Sideband Correlation Matrix (SCM)** formalism

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Cyclostationary noise formalism

- Only the spectral components in each **sideband** having the **same distance** from the LS harmonics, are **correlated**



- 2nd order statistical properties through the **sideband correlation matrix (SCM)**:

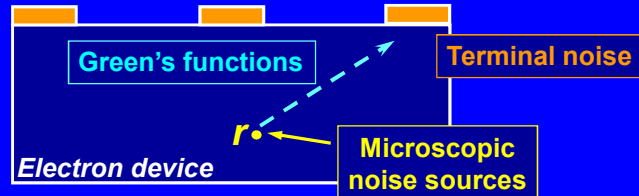
$$\left(S_{y,y}(\omega) \right)_{k,l} = \left\langle \tilde{y}(\omega_k^+) \tilde{y}^*(\omega_l^+) \right\rangle$$

ω is called **sideband frequency**

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LS cyclostationary noise - II

LS extension of
Green's function
approach

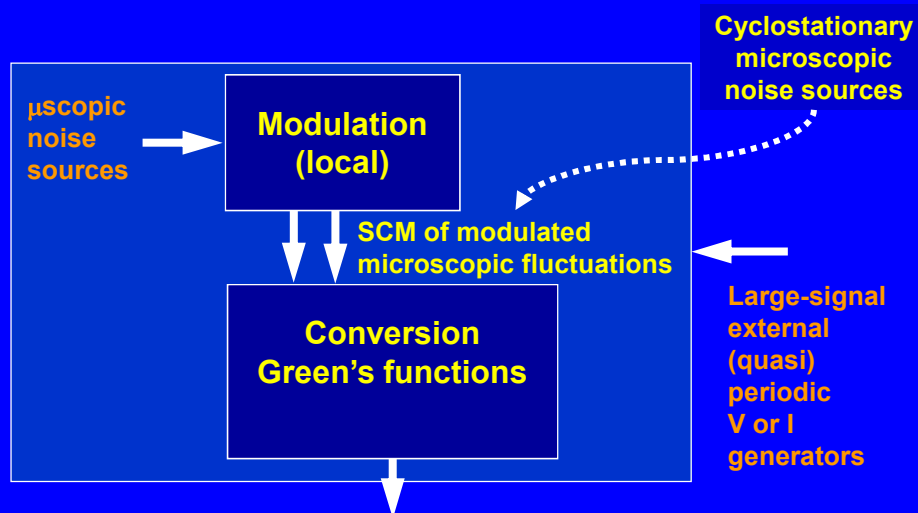


- Green's functions → **conversion** Green's functions, implying noise frequency conversion into LS spectrum sidebands
- After **propagation** & **conversion** noise around each harmonic is from
 - microscopic noise source **at that sideband**
 - source conversion **from other sidebands**

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LS cyclostationary noise - III



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Noise in autonomous systems

- **Oscillator noise** → object of investigation and debate at circuit and system level
- Alper Demir's approach (system level) accounting both for **coloured** and **white noise sources** → viable way for extension to device level
- Work by group of Seoul National University (white diffusion noise sources)

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Numerical implementation

- Through standard (e.g. finite box – Scharfetter-Gummel) discretization the Green's function is derived from a **linear system** (← SS or SSLs)
- Efficient evaluation of the Green's functions at device terminals through **adjoint** and **generalized adjoint** techniques
- ☹ **Bottleneck**: LS (quasi) periodic solution through Harmonic Balance

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Low frequency noise modelling

- **Low-frequency** (coloured, $1/f$ or **Lorentzian**) noise important in many analog applications (mixers, multipliers, oscillators...) where noise frequency conversion takes place
- Low-frequency noise \rightarrow superposition of **bulk, surface or interface GR noise**
- **GR trap-assisted** noise \rightarrow theory developed by van Vliet in 1960 \rightarrow **trap level rate equations** added to DD model

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Model + traps: bipolar drift-diffusion

- N_t **traps** included
- Device **mesh**: N_i internal nodes and N_x external nodes on metallic contacts
- Device **contacts**: N_c+1 , one grounded

$$\nabla^2 \phi = -\frac{q}{\epsilon} \left(p - n - \sum_{k=1}^N n_{t,k} \right)$$

$$\frac{\partial n}{\partial t} = -\nabla \cdot (n \mu_n \nabla \phi - D_n \nabla n) - U_n + \gamma_n$$

$$\frac{\partial p}{\partial t} = +\nabla \cdot (p \mu_p \nabla \phi + D_p \nabla p) - U_p + \gamma_p$$

$$\frac{\partial n_{t,k}}{\partial t} = -U_k + \gamma_k \quad k=1, \dots, N$$

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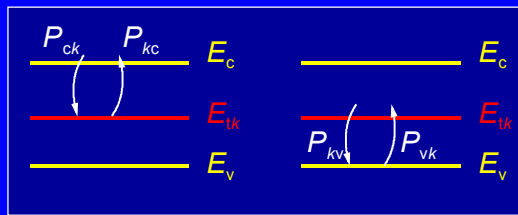
Trap level transition rates

- N (local) trap rate equations \rightarrow SRH model
- **Noninteracting traps** considered;
superposition \rightarrow **1/f spectrum**

total trap density $c = (\text{cross sect.}) \times v_{th}$

$$P_{ck} = c_{n,k} n (N_{t,k} - n_{t,k}), \quad P_{kc} = c_{n,k} n_{t,k} n_{t,k},$$

$$P_{vk} = c_{p,k} p_{l,k} (N_{t,k} - n_{t,k}), \quad P_{kv} = c_{p,k} p n_{t,k}$$



$$n_{t,k} = N_c \exp\left(\frac{E_{t,k} - E_c}{k_B T}\right)$$

$$p_{l,k} = N_v \exp\left(\frac{E_v - E_{t,k}}{k_B T}\right)$$

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SS - RG local noise source

$$K_{\gamma_n, \gamma_n} = 2(P_{ck0} + P_{kc0}),$$

$$K_{\gamma_p, \gamma_p} = 2(P_{vk0} + P_{kv0}),$$

$$K_{\gamma_n, \gamma_p} = 0,$$

$$K_{\gamma_k, \gamma_k} = 2(P_{ck0} + P_{kc0} + P_{vk0} + P_{kv0}),$$

$$K_{\gamma_n, \gamma_k} = -2(P_{ck0} + P_{kc0}),$$

$$K_{\gamma_p, \gamma_k} = 2(P_{vk0} + P_{kv0})$$

$\gamma_n \rightarrow$ Langevin source,
e-continuity equation

$\gamma_p \rightarrow$ Langevin source,
p-continuity equation

$\gamma_k \rightarrow$ Langevin source,
 k th trap rate equation

**Trap transition
probabilities**

$$P_{ck} = c_{n,k} n (N_{t,k} - n_{t,k}),$$

$$P_{kc} = c_{n,k} n_{t,k} n_{t,k},$$

$$P_{vk} = c_{p,k} p_{l,k} (N_{t,k} - n_{t,k}),$$

$$P_{kv} = c_{p,k} p n_{t,k}$$

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LS - RG local noise source SCM

- In LS conditions the white microscopic RG noise sources are **(quasi) periodically** modulated by the working point
- Noise source SCM, e.g.:

$$\left(\mathbf{K}_{\gamma_n, \gamma_n} \right)_{l,m} = 2 \left(P_{ck0,l-m} + P_{kc0,l-m} \right)$$

.....etc.

**(l-m)-th Fourier component
of transition rate**

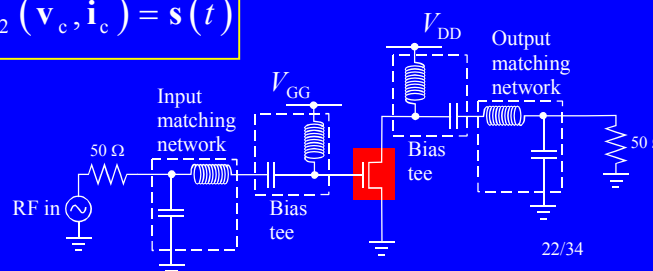
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Solving the PB model in LS: the embedding circuit

- Represented, in its simplest form, by a **memory relationship** between v_c , i_c and the applied generators $s(t)$
 - For **periodic excitation**, $s(t+T)=s(t)$
 - For **autonomous circuit**, $s(t)=0$

$$\frac{d}{dt} \mathbf{e}_1(v_c, i_c) + \mathbf{e}_2(v_c, i_c) = \mathbf{s}(t)$$



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Solving the PB model in LS: total discretized model & solution

- (Space) discretized PB model + embedding circuit → **differential algebraic equation (DAE)**

System size:
$$N_{\text{eq}} = (3 + N_t)(N_i + N_x) + 2N_c$$

For a 3-terminal device with 2000 nodes mesh and 3 traps $N_{\text{eq}}=12,004$!

- Direct computation of the steady-state response
 - Frequency-domain: **Harmonic Balance (HB)**
 - Time-domain: **shooting method**
 - Autonomous case?

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Case studies

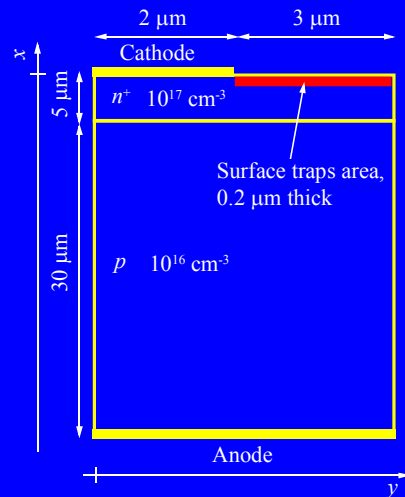
- 2D n^+p diode
 - motivation: low-frequency noise compact modelling usually based on **amplitude modulation of stationary SS noise generators** → is this generally correct / accurate?
- GaAs MESFET and AlGaAs/GaAs HEMT Mixer
 - 2D LS mixed-mode noise simulation

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2D n^+p diode

- n^+p junction diode → 1 **bulk** and 3 **surface** traps



Bulk trap:

$$N_t = 5 \times 10^{12} \text{ cm}^{-3}$$

$$c_n = c_p = 5.7 \times 10^{-13} \text{ cm}^3/\text{s}$$

energy level: 0.56 eV below E_c

Surface traps:

$$N_t = 1.67 \times 10^{16} \text{ cm}^{-3}$$

$$N_{t,\text{surf}} = 3.34 \times 10^{11} \text{ cm}^{-2}$$

energy level: 0.26 eV below E_c

Trap 1: $c_n = c_p = 5.7 \times 10^{-14} \text{ cm}^3/\text{s}$

Trap 2: $c_n = c_p = 5.7 \times 10^{-15} \text{ cm}^3/\text{s}$

Trap 3: $c_n = c_p = 5.7 \times 10^{-16} \text{ cm}^3/\text{s}$

Large-signal simulation:

6 harmonics + DC

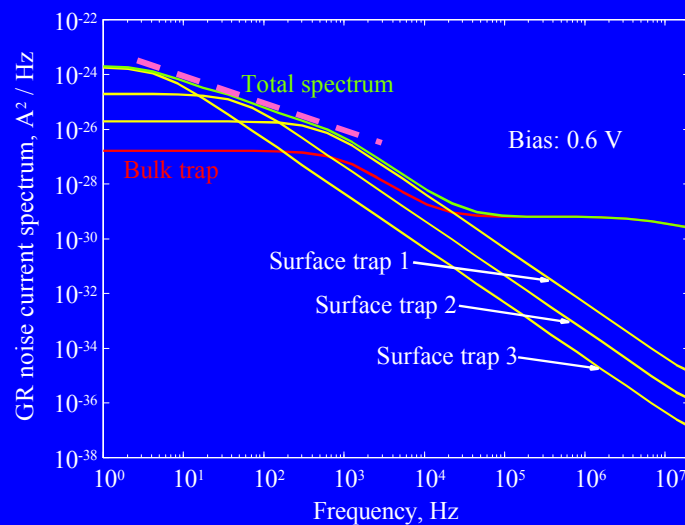
working point: 0.6 V DC

+ 50 mV tone @ 5 MHz

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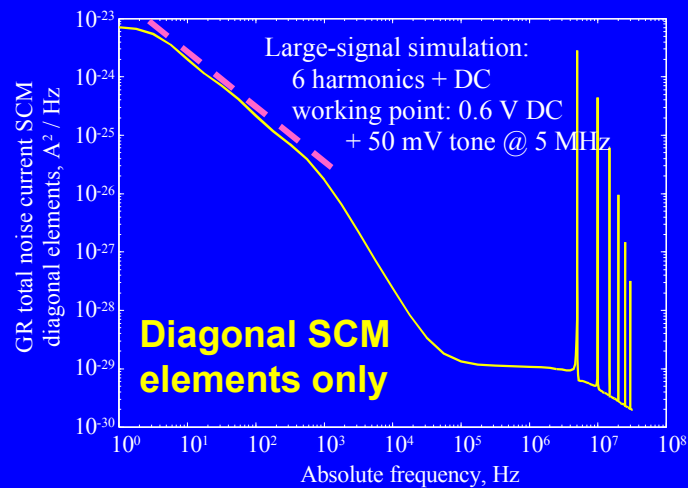
Stationary GR noise spectrum



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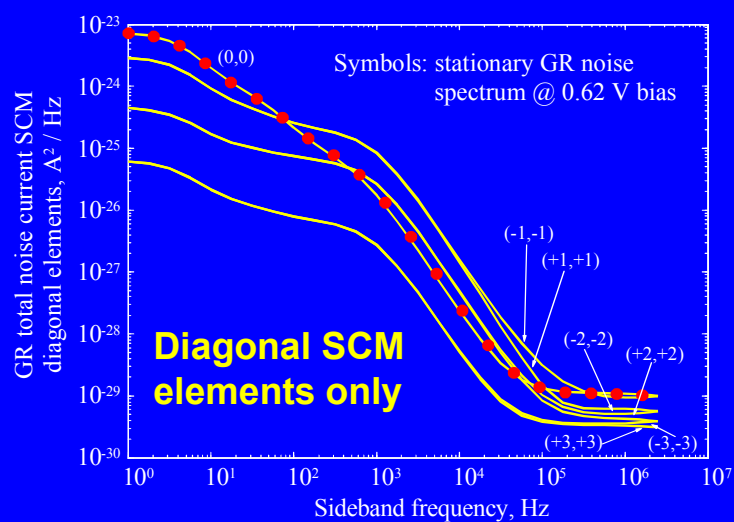
Cyclostationary GR noise spectrum (absolute frequency)



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Cyclostationary GR noise spectrum (sideband frequency)



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Remarks

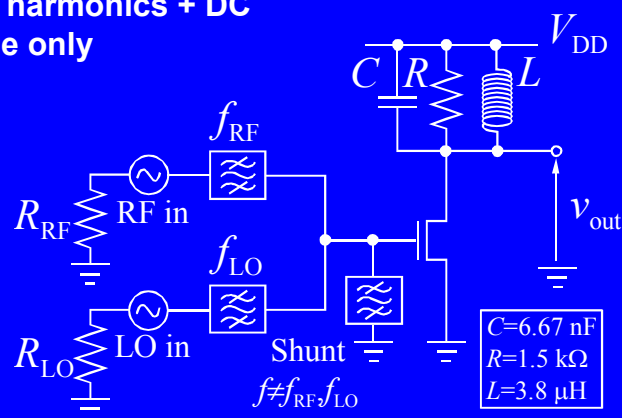
- The SS 1/f like behaviour is **preserved in the (0,0) sideband**
- However, **conversion to upper sidebands** acts **differently** for **bulk** and **surface** traps
- Therefore, noise in upper sidebands is **markedly different from modulated SS noise** → which would have the same 1/f like behaviour for all sidebands
- Impact on **compact modelling!**

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Mixer circuit

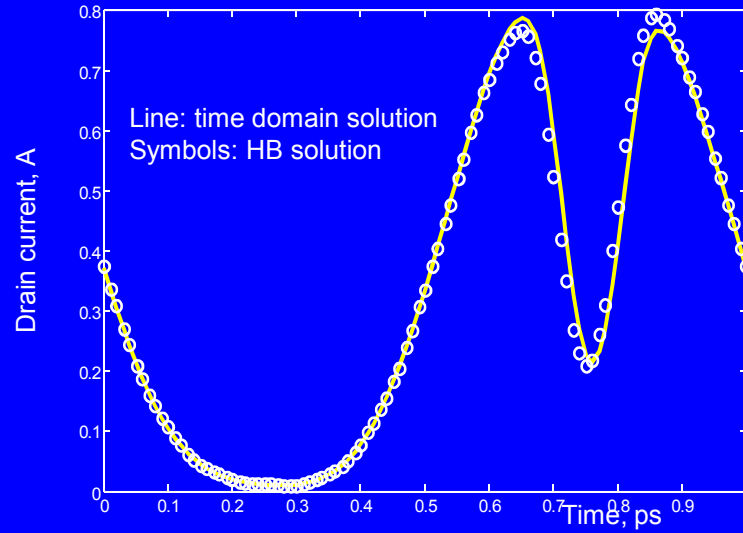
- Downconversion mixer, $f_{LO}=1$ GHz, $f_{RF}=1.001$ GHz
- Noiseless LO
- Device: 0.3 μm gate HEMT, 100 μm gate periphery
- 1300 nodes, 4 harmonics + DC
- Diffusion noise only



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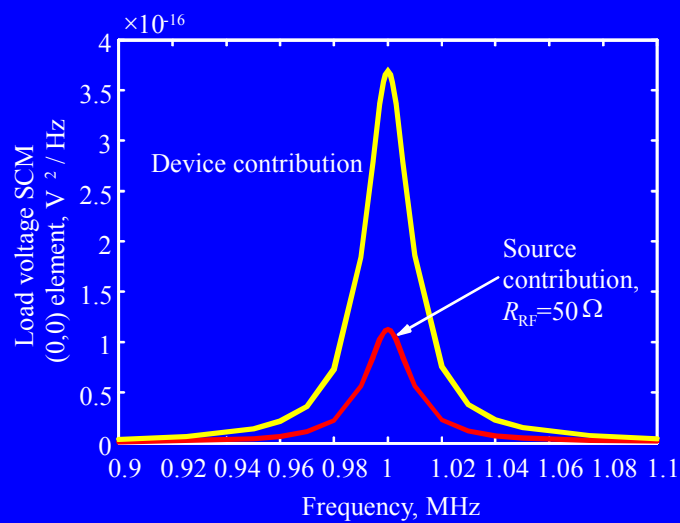
Mixer WP



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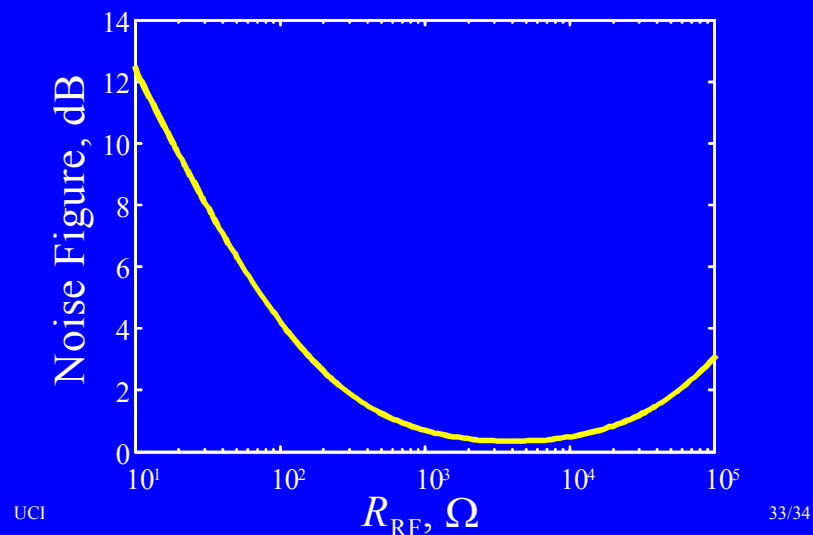
Load voltage noise around IF



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Intrinsic noise figure vs. RF source resistance



Conclusions

- Numerical noise simulation has (hopefully) reached maturity
- Progress made in understanding **low-frequency noise** ($\rightarrow 1/f$) and its **frequency conversion** (also \rightarrow compact modelling)
- Encouraging advances in **oscillator** PB modelling
- LS noise simulation requires more efficient WP solvers (time domain?)
- General strategy for LS compact modelling still an open problem – but this is another story!